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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

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Liquid Crystalline Polymer Based R/F Wireless Components For Multi-Band Applications

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Respectfully submitted,

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Liquid Crystalline Polymer (LCP) Based Lumped-Element Bandpass Filters for Multiple Wireless Applications

Abstract — **This paper presents for the first time the design, implementation, measurements and reliability data of multiple RF filters on Liquid Crystalline Polymer based substrates for different communication standards such as 802.11 a/b/g, LMDS/MMDS, cellular and Bluetooth applications. The first examples of this platform substrate technology are very compact 12mm³ fully packaged SMT front-end filters with center frequencies of 2.45 and 5.775 GHz. One embodiment of the filter at 2.45 GHz, which is well suited for 802.11 b/g and Bluetooth type applications, provides a passband of 100 MHz with maximum inband insertion loss less than 2dB at 25°C, greater than 25dB attenuation at 2700-2800 MHz, greater than 10dB attenuation below 2.2GHz, greater than 20dB rejection at the second and third harmonic and inband VSWR less than 1.5 matched to 50 Ohms at the input and output.**

Index Terms — **Bandpass Filters, Chip-type component, embedded passives, lumped element microwave circuits resonators, multilayer organic (MLO), multilayer RF circuits, packaging, printed circuit board (PCB).**

I. Introduction

Currently low-temperature co-fired ceramic (LTCC) [1-3], multilayer ceramic (MLC) [4] and ceramic monoblock technologies [5] are the prevalent choices for the implementation of surface mount components such as front-end RF passive band pass filters, duplexers and diplexers, and image reject filters. However, ceramic components and packages cannot be integrated into the inner circuit layers of printed circuit boards (PCBs) and have to be implemented as discrete components increasing reliability concerns and mounting costs. Integration of high performance passives such as filters, in organic substrates or the PCB helps reduce module surface area, saves cost and increases reliability. The work done in [6-13] illustrates organic process technologies, similar to PCB technologies, that are being targeted as a cost-effective alternative to the primary technologies of choice namely ceramic based devices mentioned earlier. The work done in [6,9-11] illustrates example of filters implemented using lumped element and transmission line topologies to realize components at 2.4GHz, 5GHz and 1.9GHz. However, organic implementations may suffer from excessive insertion loss, insufficient attenuation, large size, variability due to changes in humidity or temperature and EMI. This paper presents the design of novel fully packaged miniature bandpass filters using Liquid Crystalline Polymer (LCP) based substrates. The components offer five distinctive features 1) since these are implemented using a hybrid coplanar waveguide (CPW)/stripline topology they are completely shielded on all sides except the sides used as input/output terminals thus minimizing radiation losses and EMI interference, 2) using a combination of lumped and distributed elements and coupling between components in multilayer substrates provides size reduction on the order of $\lambda/40$, 3) low insertion loss comparable to ceramic monoblock filters and LTCC filters for comparable size, bandwidth and attenuation specifications, 4) a high reliability prove by extensive life testing, and 5) minimal temperature dependence performance variation. The paper has been organized as follows: section II discusses the design of filters followed by section III which discusses measurements of filters and model to hardware correlation; finally, section IV discusses the manufacturing variability and reliability data for devices.

II. Design of Filters

Different filters have been implemented using the circuit configuration shown in Fig. 1. It consists of a second order coupled resonator bandpass filter (with capacitive coupling, CM, and inductive coupling, LM) in parallel with a feedback capacitor, C-Inter-Resonator. A primary attenuation pole in the lower or upper stopband is achieved by using the parallel resonator formed by a combination of elements LM and CM. The purpose of the feedback capacitor is to alter the location of this primary zero by bringing it closer to the passband for increased steepness/roll-off and to introduce another transmission zero. Variants of this design schematic have been demonstrated in [2,3,7,and 9]. This paper further extends by adding lowpass filter elements at the input and output to achieve high attenuation at the second harmonic and third harmonic of the center frequency. Using the resonant property of lumped capacitors C1 and C2, which resonate with parasitic inductances LC1 and LC2 respectively, could also do this. For simplicity the only parasitic

components of capacitors, C1 and C2 have been shown in Fig. 1. The circuit prototypes were first simulated in Agilent's ADS circuit simulation tool to estimate the Qs required for the individual components. Once the Qs are estimated, topologies similar to those demonstrated in [7,8,12,and 13] by the authors were used as the guidelines for the design of stand alone components. Inductors in the range of 1nH-10nH [7,8] can be embedded in stripline, CPW, microstrip or a combination of the above with Qs in the range of 30-200 based on the topology and configuration used. Using low loss (ε_r=2.9, tan δ=0.002 below 10GHz) 1mil thick LCP for embedded parallel plate capacitors or inter-digital capacitors helps achieve unloaded Q>200 for capacitances in the range of 0.1-5pF for frequencies >2GHz with capacitance densities on the order of 2pF/mm^2. Generally speaking, the highest Qs are required for the capacitors and inductors that form the resonant tanks namely L1, C1 and L2, C2 to achieve the lowest insertion loss in the passband. A combination of high Q inductors and low loss LCP type substrates make it possible to achieve unloaded Qs upwards of 100 for lumped resonators, which is comparable to the unloaded Qs of larger transmission line resonators such as quarter wave resonators with a tenfold size reduction. The first filter designed was for the intermediate frequency (IF) stage for a 100Mbps local multipoint distribution system (LMDS) operating at 14GHz and the IF stage at 2.4GHz. A filter with component values of L2=L1=1.93nH, C1=C2=1.57pF, CMatch=0.538pF, and CM=0.213pF was designed to meet the desired specification of a 1dB passband of 120MHz with ± 0.25ns group delay variation and maximum insertion loss of 2.5dB in the passband with >50dB attenuation below 1GHz. (All other components shown in Fig. 1 exist as parasitics of the primary components and the package itself). The group delay variation specification is required to minimize distortion of large data through the passband. This filter could also be used for 802.11b/g and Bluetooth standards. Figure 2 shows the metal structure with components in the two inner packaging layers. (The top and bottom solid ground planes are sufficiently far away from the inner layers and act as signal line references). The ends of inductors L1, L2 and bottom plates of capacitors C1, C2 (all bottom plates shown as dotted lines) are connected to the top and bottom plates using through hole vias commonly used in PWB processing. This results in a CPW/stripline topology with the side walls acting as CPW grounds and the bottom and top plates as stripline references. This provides an EMI shield on all sides except the sides with input and output ports. The layout for this particular device is done in such a manner that the coupling between L1 and L2 cancels out the coupling between C1 and C2. Fig. 3 shows the ADS [14] circuit simulation (solid lines) and ANSOFT HFSS [15] layout simulation (sampled data). As seen in Fig. 3 the simulations meet the desired specifications and achieve much lower insertion loss of <2dB within the passband specified with a filter size of 15mm^3. A second filter intended for WLAN front-end RF filter type applications was designed using the same design methodology as discussed earlier. The circuit filter response (solid lines) and HFSS layout simulation (sampled data) are shown in Figure 4. The filter has a 1dB passband of 100MHz with insertion loss less than 2dB from 2.4-2.5GHz, transmission zeroes at 2.8GHz and 1.6GHz and greater than 20dB rejection of the second and third harmonics and below 2.1 GHz. Compared to the previous filter this filter layout measured a nominal 12mm^3. The discrepancy between the circuit model and full-wave HFSS data in Fig. 4 is due to the presence of many more components in this design compared to the previous one. This needs to be modeled as distributed transmission line components and cannot be accurately modeled using lumped equivalents shown in Fig. 1. Fig. 5 shows ADS circuit simulation data (solid lines) and HFSS data (sampled data) for a 5.7GHz filter for 802.11a application. The filter has a 1dB passband of 100MHz with insertion loss less than 2.6dB from 5.725-5.825GHz, transmission zeroes at 6.1GHz and 5.1GHz and greater than 10dB rejection of the second and third

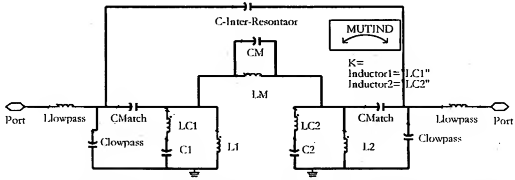

Fig. 1. Schematic of 2 pole second-order filter with two transmission zeroes and enhanced 2nd and 3rd harmonic rejection

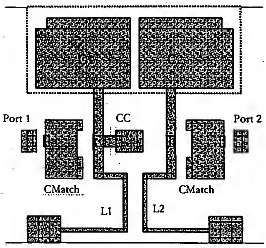

Fig. 2. Realized embedded filter structure with top and bottom ground planes

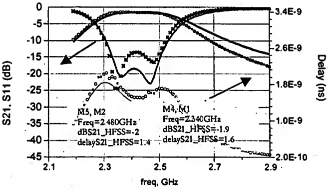

Fig. 3. Filter response simulated in HFSS and ADS for filter shown in Fig. 2

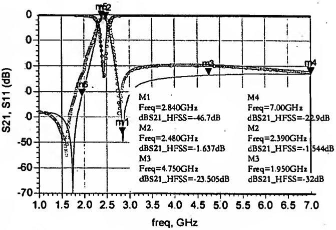

Fig. 4. Filter response simulated in HFSS and ADS for WLAN (802.11b) Applications

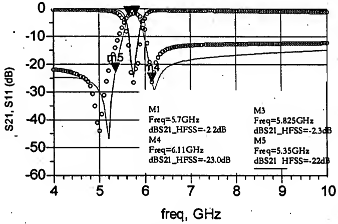

Fig. 5. Filter response simulated in HFSS and ADS for WLAN (802.11a) Applications

harmonics. This filter measures 12mm^3. The design methodology can be easily applied to filters with more than two resonant tanks to provide additional zeros and broader passbands. The next section shows measurement data for 2.4GHz and 5.7 GHz filter discussed in this section.

II. Measurements

The devices were fabricated and tested using Agilent's 8720 ES Vector Network Analyzer after performing SOLT calibration. Fig. 6 shows HFSS data and measured data for two of the three filters discussed earlier. The figure illustrates very good correlation between modeled and measured S_{11} (return loss) and S_{21} (insertion loss) for the filters.

IV. Manufacturing Tolerances and Reliability

Typical design rules for PWB technology such as 3mil (75um) lines with 3mil spacing, 10mil (250um) through holes have been used in the fabrication of these filters. The filters have been fabricated on panel sizes as large as 12 inches x 18 inches. The measured results show little variation from device to device namely a worst-case center frequency variation of ±15MHz for approximately 60% of the devices.

The devices successfully passed extensive reliability testing including liquid-to-liquid thermal shock (1000 cycles at -55°C to 125°C), temperature humidity (85°C, 85%RH), and high temperature aging (1000 hours at 125°C) without any failures. The devices were also characterized from 0°C - 85°C and an increase in insertion loss by approximately 0.2dB.

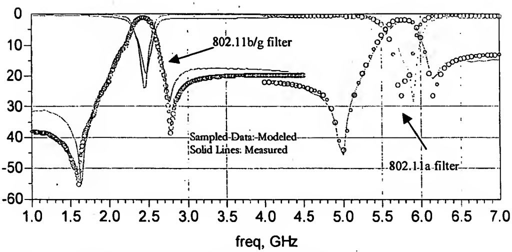

Fig. 6. Comparison of full-wave EM simulation and the measurement of 2.4 (802.11b/g)a and 802.11a prototype filters with the proposed configuration

V. Conclusion

A novel design methodology and the use of a novel multilayer organic LCP based process helps realize very compact front-end which meet the requirements of multiple standards and applications with excellent harmonic suppression. The design enables complete EMI shielding and packaging of the devices in large panel format without the need for expensive post-processing steps. The devices can be configured as microBGA [8], and SMT packages (as shown in this paper) or integrated on-package passives [8]. SMT components with input/output and ground terminals can be finished with Ni/Au, solder, tin, silver or other popular surface metallurgies. Design for other RF components such as diplexers/duplexers and baluns have been completed and fabricated and show comparable performance to similar LTCC, MLC and monoblock based devices with the same size profile.

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Liquid Crystalline Polymer Based RF/Wireless Components for Multi-Band Applications

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Abstract

This paper presents for the first time the design, implementation, measurements, reliability data and integration of multiple RF components such as filters, baluns, diplexers, and a combination of the above on Liquid Crystalline Polymer (LCP) based substrates for communication standards such as 802.11 a/b/g, LMDS/MMDS, satellite/digital TV, UWB, cellular and Bluetooth type applications.

These components and process technologies are being targeted as a cost-effective high-performance, miniaturized alternative to the primary technologies of choice for multi-band RF/wireless applications, namely, low-temperature co-fired ceramic (LTCC), multi-layer ceramic (MLC) and ceramic monoblock technologies.

The first examples of this platform substrate technology are very compact 12mm^3 fully packaged SMT front-end filters with center frequencies of 2.45, 5.25 and 5.775 GHz. One embodiment of the filter at 2.45 GHz, which is well suited for 802.11 b/g and Bluetooth type applications, provides a passband of 100 MHz with maximum inband insertion loss less than 1.7dB at 25°C, greater than 25dB attenuation at 2700-2800 MHz, greater than 10dB attenuation below 2.2GHz, greater than 20dB rejection at the second and third harmonic and inband VSWR less than 1.5 matched to 50 Ohms at the input and output.

Introduction

Currently low-temperature co-fired ceramic (LTCC) [1-3], multilayer ceramic (MLC) [4] and ceramic monoblock technologies [5] have become the prevalent choices for the implementation of surface mount components such as front-end RF passive band pass filters, duplexers, and baluns. LTCC is becoming the most popular ceramic technology since it uses miniature lumped components such as inductors and capacitors which can be optimized for operation over a wide band of frequencies whereas monoblock and MLC components use different materials for different frequencies and limits the integration of devices for multiband applications. LTCC additionally with its ability to integrate in excess of 20 layers, has quickly become a platform for the integration of front-end modules for multiband applications that combine several lumped element filters, baluns and diplexers for cellular applications and WLAN applications. It is typical for such front-end modules to consist of greater than 10-15 metal metallic layers with microvias connecting each layer, and in many instances also consists of SAW type filters and monoblock filters mounted on the multiple ceramic layers to meet the more stringent requirements of bandpass filters. The need for many layers, which does provide the needed density, translates to more design time and higher tooling cost and problems of shrinkage and performance issues. LTCC also suffers from higher costs since it cannot be manufactured in panel sizes larger than 6x6 square inches. Moreover, LTCC has lower performance due to process tolerances (10% component tolerance) and higher dielectric losses (tan δ =0.005-0.007 at 1GHz) compared to MLC and monoblock counterparts (2%-5% component tolerance and tan δ = 0.0005). This problems are becoming imminent as the personal handset market, small-office home-office (SOHO) market and consumer appliance market get crowded with multiple standards such as 802.11b/g/a, Bluetooth, Zigbee, UWB, 3G, GPS, GSM, Satellite Radios and TVs, etc., which need higher performing, smaller, cost-effective and customizable modular technology with a faster time to market. Proponents of LTCC technology are trying to alleviate these concerns

by an effort to make LTCC more cost-effective, a large area process and higher performing.

However, integration of high performance passives such as filters, in organic substrates or the PCB can eliminate the total dependence on LTCC and would help reduce module surface area, save costs and increase reliability. The work done in [6-16] illustrates organic process technologies, similar to PCB technology, that are being targeted as a cost-effective alternative to the primary technologies of choice namely ceramic based devices mentioned earlier. The work done in [6,9-11,14,16] illustrates example of filters implemented using lumped element and transmission line topologies to realize components at 2.4GHz, 5GHz, 1.9GHz and frequencies > 5GHz. However, organic implementations may suffer from excessive insertion loss, insufficient attenuation, and large size, variability due to changes in humidity and/or temperature and EMI. This paper presents the design of novel fully packaged miniature bandpass filters, baluns, diplexers and a combination of the above using Liquid Crystalline Polymer (LCP) based substrates. The components offer the following distinctive features 1) utilization of a hybrid coplanar waveguide (CPW)/stripline topology in a package that is completely shielded on all sides except the sides used as input/output terminals minimizes radiation losses and EMI interference, 2) a combination of lumped and distributed elements and coupling between components in multilayer substrates provides size reduction on the order of $\lambda/40$, 3) low insertion loss comparable to ceramic monoblock filters for comparable size, bandwidth and attenuation specifications, 4) a high reliability proven by extensive life testing, 5) minimal temperature dependence performance variation, 6) reduced number of metal layers to achieve the same density as LTCC, 7) the same substrate which can be used at multiple frequencies (1GHz-100GHz) to implement different functions such as filters, diplexers and baluns, 8) large area (18x24 square inch) processing, 9) faster time to market due to lesser number of layers and 10) reduced moisture uptake properties (0.04%) comparable to ceramics. The paper has been organized as follows: section II discusses the design of filters followed by section III which discusses measurements of filters and model to hardware correlation; section IV discusses the manufacturing variability and reliability data for devices; the design of diplexers for satellite TV type applications is presented in section V followed by section VI which discusses the work on baluns.

Design of Filters

Different filters have been implemented using the circuit configuration shown in Fig. 1. It consists of a second order coupled resonator bandpass filter (with capacitive coupling, Cmutual, and inductive coupling, Lmutual) in parallel with a feedback capacitor, CInter-Resonator. A primary attenuation zero in the lower or upper stopband is achieved by using the parallel resonator formed by a combination of elements Lmutual and Cmutual. The purpose of the feedback capacitor is to alter the location of this primary zero by bringing it closer to the passband for increased steepness/roll-off and to introduce another transmission zero. Variants of this design schematic have been demonstrated in [2, 3, 7, and 9]. This paper further extends by adding lowpass filter elements at the input and output to achieve high attenuation at the second harmonic and third harmonic of the center frequency. This could also be done by using the resonant property of lumped capacitors CRES1 and CRES2 which resonate with their respective parasitic inductances to provide transmission zeroes. For simplicity no parasitic components have been shown in Fig. 1. The circuit prototypes were first simulated in Agilent's ADS [17] circuit simulation tool to estimate the Qs required for the individual components. Once the Qs are estimated, topologies similar to those demonstrated in [7, 8, 12, and 13] by the authors were used as the guidelines for the design of stand alone components. Inductors in the range of 1nH-10nH [7, 8] can be embedded in stripline, CPW, microstrip or a combination of the above with Qs in the range of 30-200 based on the topology and configuration used. Using low loss (ε_r=2.9, tan δ=0.002 below 10GHz, and tan δ=0.003 below

100 GHz) 2mil thick LCP for embedded parallel plate capacitors or inter-digital capacitors helps achieve unloaded Q>200 for capacitances in the range of 0.1-5pF for frequencies >2GHz with capacitance densities on the order of $2pF/mm^2$. Generally speaking, the highest Qs are required for the capacitors and inductors that form the resonant tanks namely LRES1, CRES1 and LRES2, CRES2 to achieve the lowest insertion loss in the passband. A combination of high Q inductors and low loss LCP type substrates make it possible to achieve unloaded Qs upwards of 100 for lumped resonators, which is comparable to the unloaded Qs of larger transmission line resonators such as quarter wave resonators with a tenfold size reduction. The first filter designed was for the intermediate frequency (IF) stage for a local multipoint distribution system (LMDS) operating at 14GHz and the IF stage at 2.4GHz. A filter with component values of L2=L1=1.93nH, C1=C2=1.57pF, CMatch=0.538pF, and CM=0.213pF was designed to meet the desired specification of a 1dB passband of 120MHz with ± 0.25ns group delay variation and maximum insertion loss of 2.5dB in the passband with >50dB attenuation below 1GHz to support minimum data rate of 100Mbps. (All components shown in Fig. 1 do exist for this circuit also in the final layout but merely as parasitics of the primary components and the package itself). The group delay variation specification is required to minimize distortion of large data through the passband. This filter could also be used for 802.11b/g and Bluetooth standards if required. Figure 2 shows the originally designed metal structure with components in the two inner packaging layers. (The top and bottom planes are sufficiently far away from the two signal layers and act as the signal references). The ends of the inductors L1, L2 and bottom plates of capacitors C1, C2 (all bottom plates shown as dotted lines) are connected to the top and bottom plates using through hole via type drills and metal plating commonly used in PWB processing. This results in a CPW/stripline topology with the side walls acting as CPW grounds and the bottom and top plates as stripline references which facilitates itself into an EMI shield on all sides except the sides with input and output ports. The layout for this particular device is done in such a manner that the coupling between L1 and L2 cancels out the coupling between C1 and C2. Fig. 3 shows fabricated prototypes for this filter which measures approximately $15mm^3$.

The measured and modeled data for this filter is shown in Figure 4. The data was measured after performing a short-open-load-thru (SOLT) calibration on a Agilent 8720ES network analyzer. The planar layers for the filter were simulated using SONNET [18] and the package parasitics were extracted using ANSOFT HFSS [19]. The final circuit simulation for the packaged component was done in ADS. The modeled data collected in this fashion is shown in Figure 4. As seen in Fig. 4 the measured data meets the desired specifications and achieves an insertion loss of <1.75dB within the passband specified with a filter size of $15mm^3$. A second design intended for 2.4 GHz WLAN front-end RF filter type applications was designed using the following lumped element components: LRES1=LRES2=5.1nH, CRES1=CRES2=0.9pF, Lmutual=26nH, Cmutual=0.088pF, CMatch=0.3pF, CLowpass=0.52, Llowpass =0.35nH and C-Inter-resonator=0.05pF. The measured filter response is shown in Figure 5. The filter depicts a 1dB passband of 100MHz with insertion loss less than 1.7dB from 2.4-2.5GHz, transmission zeroes at 2.8GHz and 1.6GHz and greater than 20dB rejection of the second and third harmonics and below 2.1 GHz. Compared to the previous filter this filter after fabrication measured a nominal $12mm^3$. Fig. 5 also shows measured data for a 5.7GHz filter for 802.11a application. The filter depicts a 1dB passband of 100MHz with insertion loss less than 2.3dB from 5.725-5.825GHz, transmission zeroes at 6.1GHz and 5.1GHz and greater than 10dB rejection of the second and third harmonics. This filter also measures 12mm3.

The following section discusses the optimization of filters with an example of a 5.2GHz filters simulated using the same methodology mentioned earlier. Figure 6 shows responses for two 5.2 GHz filters, filter A and

filter B, with the same passband characteristics but with different locations for the upper transmission zeroes. The design for Filter A has a larger Cinter-resontor capacitance than that for Filter B which brings the upper transmission zero closer to the passband by 20 MHz in Filter A. However, this has a adverse effect on the rejection of the 2nd harmonic for filter A and is corrected by adding lowpass elements at each end of the filter. On the other hand, even in the absence of the extra components, Filter B achieves similar rejection at the 2nd harmonic.

Finally, it is worth mentioning that the results presented thus far are for two pole resonator designs but can be easily extended to filters with additional poles when additional zeros and different passband characteristics are required.

Manufacturing Variability and Reliability

Typical design rules for PWB technology such as 4mil (75um) lines with 4mil spacing, 10mil (250um) through holes have been used for the fabrication of these filters. The filters have been fabricated on panel sizes as large as 12 inches x 18 inches and current results show little variability from device to device namely a worst case center frequency variation of ±15MHz for approximately 60% of the devices.

The devices successfully passed extensive reliability testing including liquid-to-liquid thermal shock (1000 cycles at -55°C to 125°C), temperature humidity (85°C, 85%RH), and high temperature aging (1000 hours at 125°C) without any failures and the devices also showed minimal change in the frequency response after these tests. The devices were also characterized from 0°C - 100°C and showed no change in the frequency response apart from an increase in insertion loss by approximately 0.2dB which can be attributed to the increase in metal resistivity losses of copper over temperature used to circuitize the inner layers. Figure 7 shows measured responses for a variation of the filter in Figure 3 over a temperature range of 10°C-100°C. As seen there is minimal shift in the passband and only a slight increase in insertion loss.

Design of Diplexers

Diplexers are an essential component in todays multiband systems and perform a multitude of functions. In some instances they help isolate transmit and receive channels, and in other cases separate bands at different carrier frequencies for different receiver channels. In this section, the authors begin by providing an example of a diplexer for use in the IF stages of satellite TV systems which helps isolate different channels. The performance required is as follows: channel 1 passband of 900-1450 MHz with insertion loss less than 3dB and stopband rejection of >40dB from 1650-2100MHz; channel2 passband of 1650-2100MHz respectively with insertion loss less than 3dB and stopband rejection of >40dB from 900-1450MHz. This type of a diplexer has usually been implemented using a ceramic monoblock device; however, in order to reduce costs it is also implemented using discrete lumped components (chip capacitors and inductors). Figure 8 shows the complexity of the circuit required to implement such a response using lumped components.

The entire circuit was designed using the same layers and same cross-section used for design of the bandpass filters discussed earlier. The resultant size for the finished component was approximately 20mm x 5mm x 2mm. Some common ceramic monoblock diplexers used for such applications are on the order of 35mm x 12mm x 5mm.

The measured data for the diplexer is shown in Figure 9. The insertion loss within the passband is <3dB and the attenuation of the respective bands meets the specifications listed earlier.

Another example of a diplexer, but with relaxed specifications, such as those for multiband 802.11a/b front-end is shown ahead. Figure 10 shows data for a 2.45/5.5GHz lowpass/highpass diplexer which attenuates the respective stopbands by >30dB and common

port return loss <12dB. This device is also laid out using the same number of layers as the bandpass filters and measures 2mmx2mmx1mm. Compared to the diplexer in Figure 8, this device uses only 7 lumped components.

Design of Baluns

Baluns are becoming an important component in the front-end of RF receivers especially those which contain an integrated differential low-noise amplifier as the very first active component. The balun is used to convert a single ended signal from the bandpass filter that follows the diplexer and antenna to a balanced differential signal for the input to the LNA. Since on-chip baluns and transformers take up valuable real estate and are limited in terms of performance due to poor Qs, an off-chip miniature balun with low loss and good phase and amplitude balance becomes very important. Lattice type baluns such as the one shown in Fig 11 are ideal for narrowband applications such as 802.11b/g where the operating frequency is 2.45GHz ± 50MHz. For larger bandwidth applications such as 802.11a where the operating frequency is 5.4 ± 500MHz the schematic shown in Fig. 12 has been used.

The lumped element circuits in Figures 11 and 12 were designed using five metal layers which includes the top and bottom ground planes. The resultant size for the finished component was approximately 2mm x 1mm x 1.5mm. This compares well with LTCC type baluns which use in excess 10 layers to achieve the same size and performance.

Figures 13 and 14 show data for a 2.4GHz balun and 5.4GHz balun, respectively. The response in Figure 13 is an example of a balun in Figure 11 whereas the response in Figure 14 is an example of a balun in Figure 12. The data for the narrowband balun in Figure 13 shows a worst case amplitude imbalance of ±0.75dB in 2.45GHz ± 50MHz and a corresponding phase imbalance of ±2 degrees. The data for the wideband balun in Figure 14 shows a worst case amplitude imbalance of ±0.75dB in 5.4GHz ± 500MHz and a corresponding phase imbalance of ±2 degrees.

The authors have also shown the feasibility for multiband baluns and multiband filters which offer the same functionality at two different frequencies. An example of multiband balun which operates as a balun at 2.4 and 5.5 GHz with the required bandwidths has been shown in [21], which is also being presented at the same venue as this paper.

Conclusions

Although, this paper discusses work done primarily on passives on LCP based substrates, the authors have shown the application of this technology to realize other components such as single and multiband oscillators [12,20], low-noise amplifiers (LNAs) [13].

This novel design methodology and process technology is very scalable and can be used to implement discrete components, integrated passive devices and RF modules without significant change in the materials, processes, and design topologies. The design enables complete EMI shielding and packaging of the devices in large panel format without the need for expensive post-processing steps. The devices can be configured as microBGA, and SMT packages (as shown in this paper) with input/output and ground terminals that can be finished with Ni/Au, solder, tin, silver or other popular surface metallurgies. Finally, designs for RF components such as diplexers, baluns and filters presented in this paper demonstrates the existence of a high performing, low-cost and large area technology alternative to ceramic technologies.

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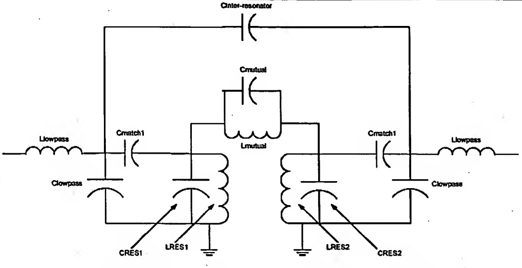


Figure. 1. Schematic of 2 pole second-order bandpass filter with two transmission zeroes and enhanced 2[nd] and 3[rd] harmonic rejection

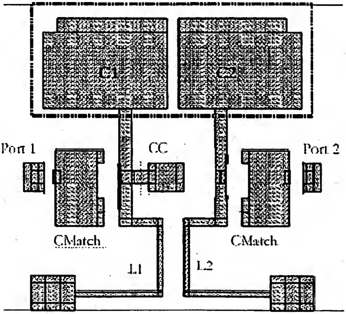


Fig. 2. Inner metal layers for 2.4GHz filter

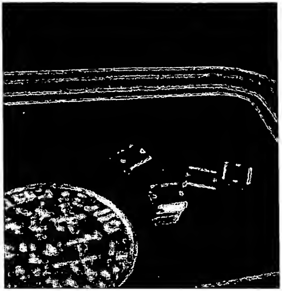


Fig. 3. Fabricated 2.4GHz filters for Bluetooth, 802.11 b/g type applications

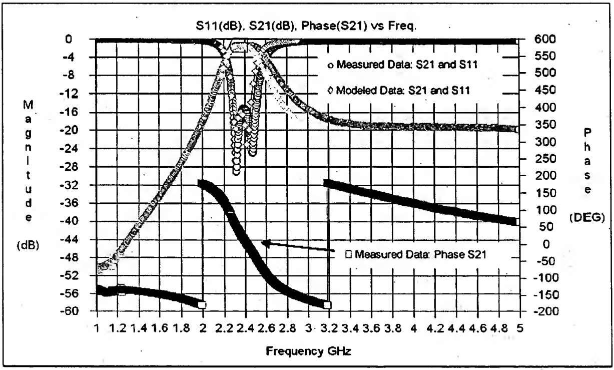


Figure 4. Measured and modeled data 2.4GHz filter shown in Figure 1.

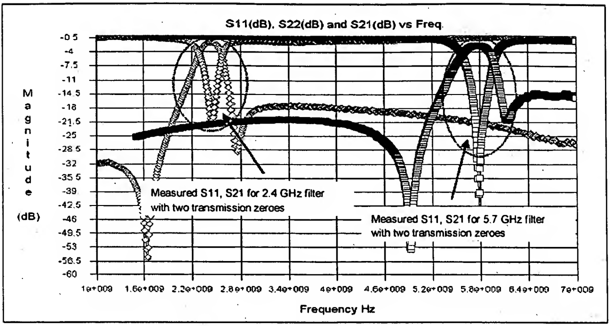


Figure 5. Measured data for 2.4GHz and 5.7GHz filters with two transmission zeroes each

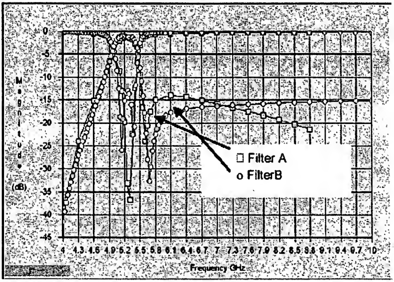


Figure 6. S11 and S21 for two 5.2 GHz filters

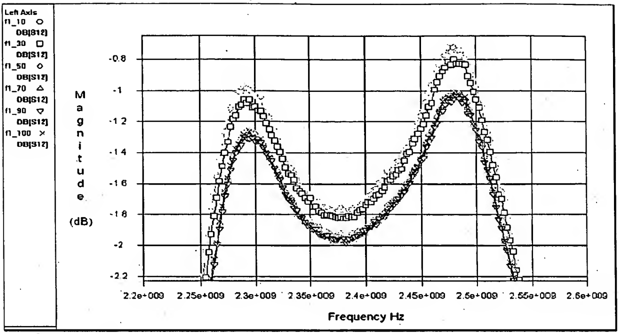


Figure 7. Responses for 2.4 GHz filter in Figure 3 over a temperature range of 10-100

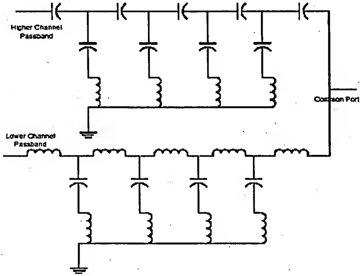


Figure 8. Lumped element diplexer implemented for Satellite TV application

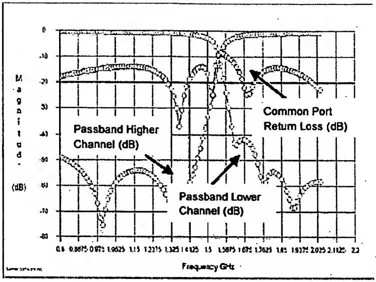


Figure 9. Data for Satellite TV diplexer

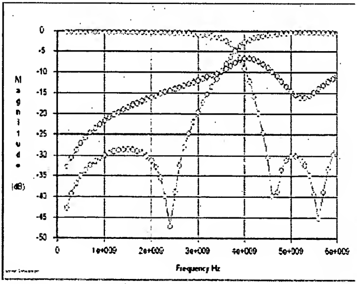


Figure 10. Data for 2.4/5.5 GHz diplexer for dual band 802.11a/b/g applications

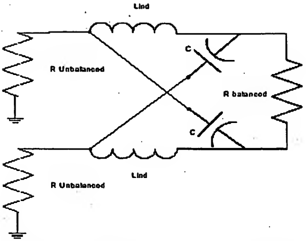


Figure 11. Lattice balun for narrowband applications

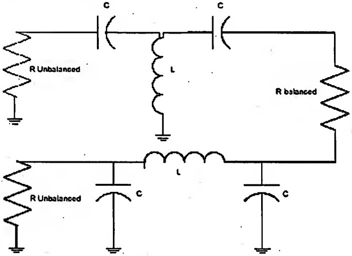


Figure 12. Lumped balun for broadband applications

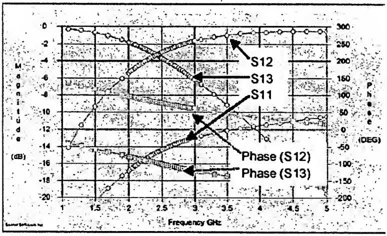


Figure 13. Response for a 802.11b/g type balun

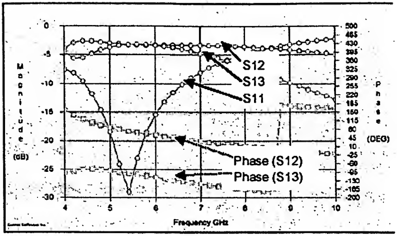


Figure 14. Response for a 802.11a type balun

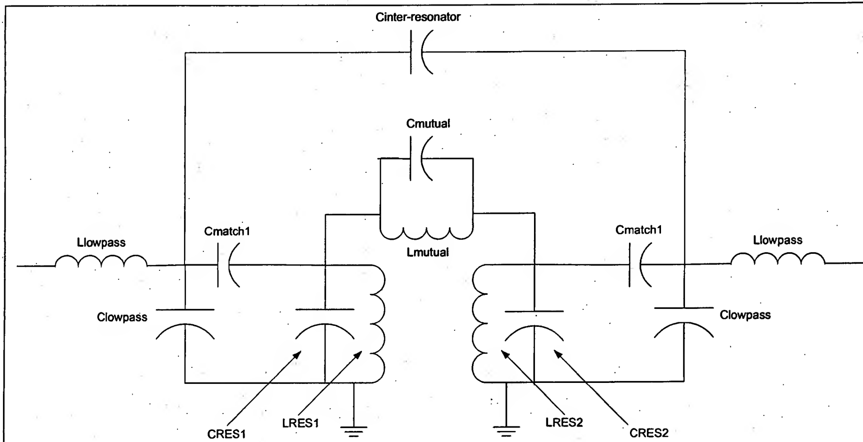
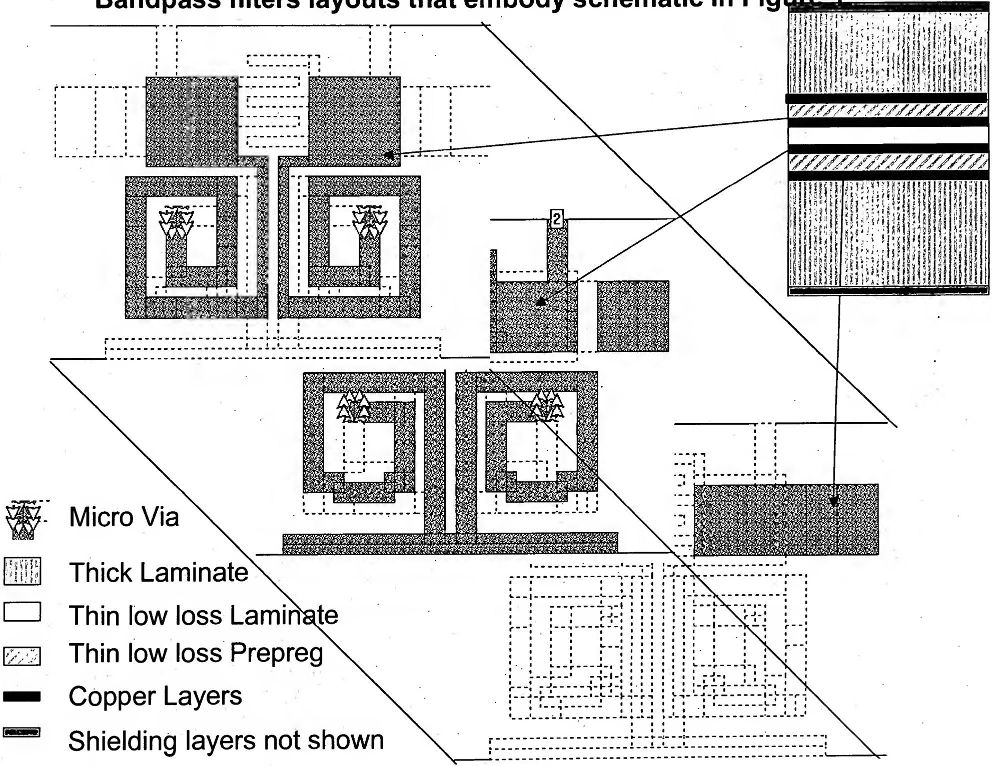
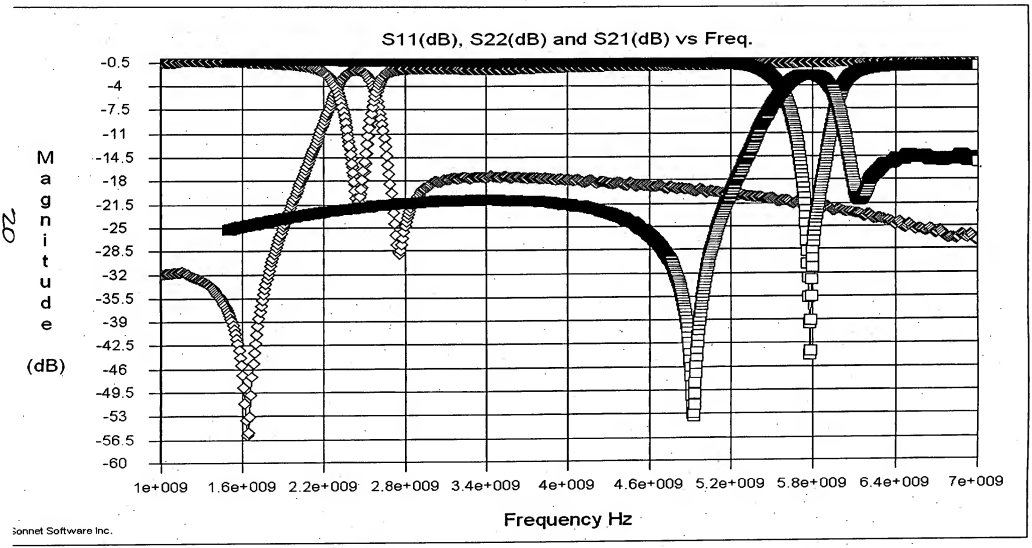


Figure. 1. Schematic of 2 pole second-order bandpass filter with two transmission zeroes and enhanced 2nd and 3rd harmonic rejection

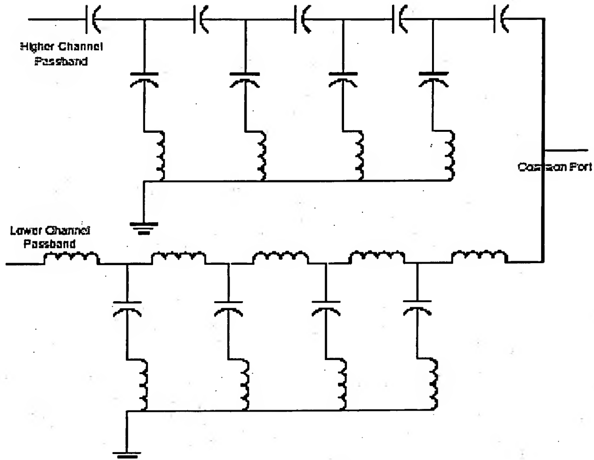
Bandpass filters layouts that embody schematic in Figure 1



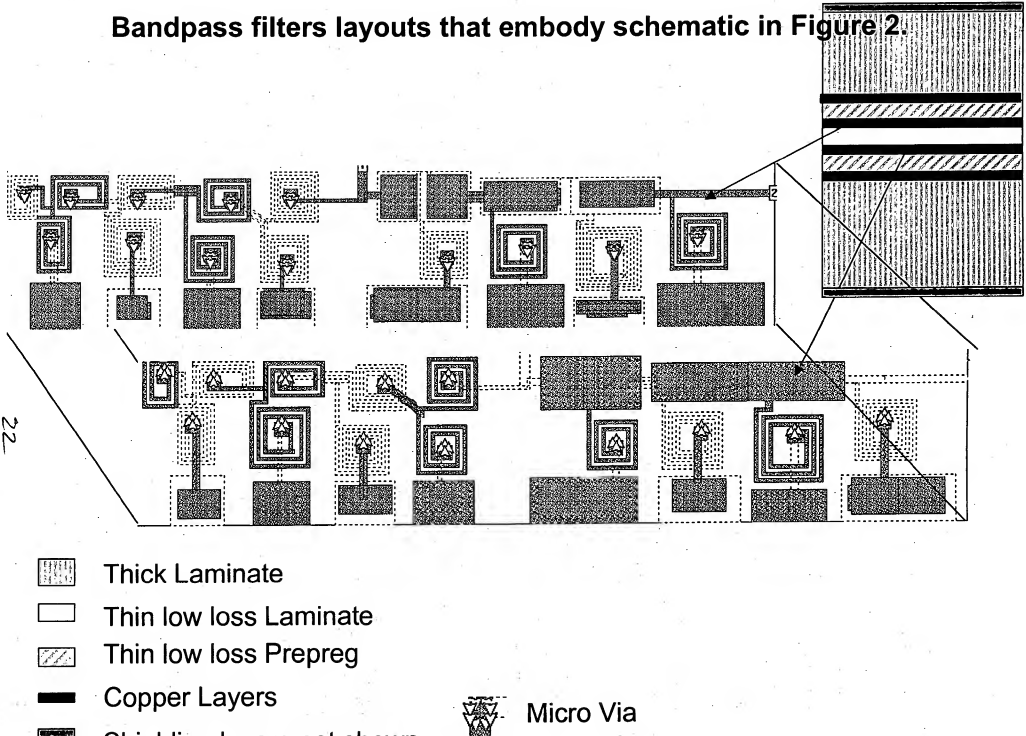
New Measured data



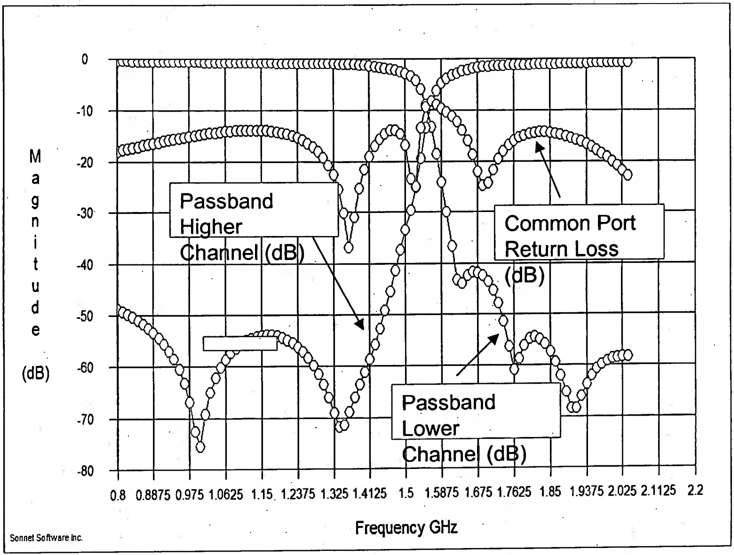
Diplexer Schematic



Bandpass filters layouts that embody schematic in Figure 2.



New Measured data for Diplexer



Data for Satellite TV diplexer